

Structural Engineering Aspects of World Trade Center Collapse

An Online Continuing Education Course for Engineers

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Structural Engineering Aspects of World Trade Center Collapse

Chelliah Sundararajan, Ph.D.

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1. INTRODUCTION

On September 11, 2001, terrorists flew two hijacked commercial airplanes into the twin towers of the World Trade Center (WTC) in New York City. The North Tower is referred as WTC1 and the South Tower as WTC2. The two towers collapsed killing some 2,800 people and causing over \$50 billion property damage.

In 2002, United States government asked the National Institute of Standards and Technology (NIST) to conduct a building and fire safety investigation into the disaster. NIST staff and hired consultants carried out the investigation. Final report on the collapse of WTC1 and WTC2 was issued on October 26, 2005; it consists of 43 documents totaling some 10,000 pages. ("Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers", NIST, 2005.) This course summarizes the key findings relating to structural engineering from those 43 documents and some related background materials from other reports.

2. STRUCTURAL DESCRIPTION

Port Authority of New York and New Jersey (PANYNJ) owned the twin towers. Each tower was 110 stories high. They were similar but not identical. Roof level of WTC1 was

1,368 feet above the concourse level; WTC2 was 1362 feet. WTC1 had a 360 feet tall radio and television transmission antenna at the roof.

The towers were built as "framed tubes"; the exterior tube connected to an interior tube through the floor system. Elevators and stairs were housed inside the interior tube (core). The building had a square footprint of 207 feet 2 inch sides.

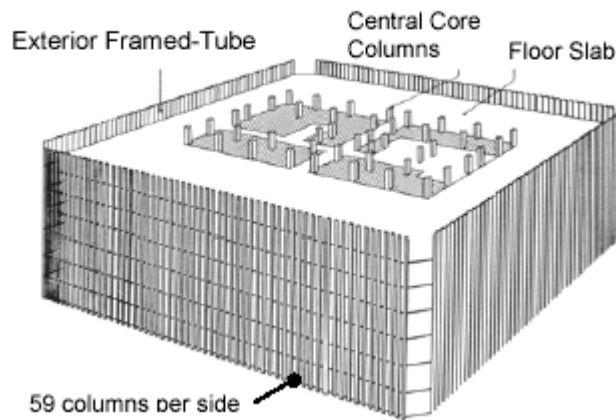


Figure 1: Building Configuration

The exterior tube consisted of box-shaped welded steel columns connected by spandrel plates (spandrels) around the perimeter at each floor level. (That is, adjacent columns were interconnected at each floor level by spandrel plates.) Typically these plates were 52" deep. (See Figure 1) Each building face consisted of 59 columns spaced at 3 feet 4 inches. These columns were designed to resist 100 percent of the lateral loads and about 50 percent of gravity loads. Below floor 7, the columns were combined in groups of three to form single base columns that were spaced 10 feet. The external cladding, which covered the columns and spandrels, consisted of aluminum sheets. The columns were founded on bedrock at 65 feet below the surface.

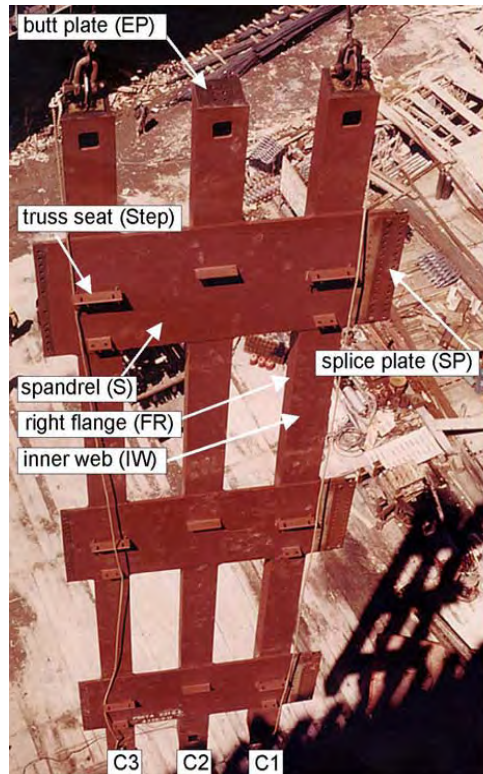


Figure 2: Columns and Spandrels

The core (87 feet by 137 feet) consisted of columns interconnected with beams. Welded box columns were used for the lower floors and rolled wide flange shapes were used for the upper floors. They were designed to support about 50 percent of gravity loads; in the lower part of the towers, the outer core columns were designed to resist a portion of the lateral forces. The core columns were also founded on bedrock at 65 feet below the surface.

The composite floor system that connected core columns and perimeter columns consisted of a grid of steel trusses integrated with concrete slab. Four-inch thick lightweight concrete slabs were laid on a fluted steel deck.

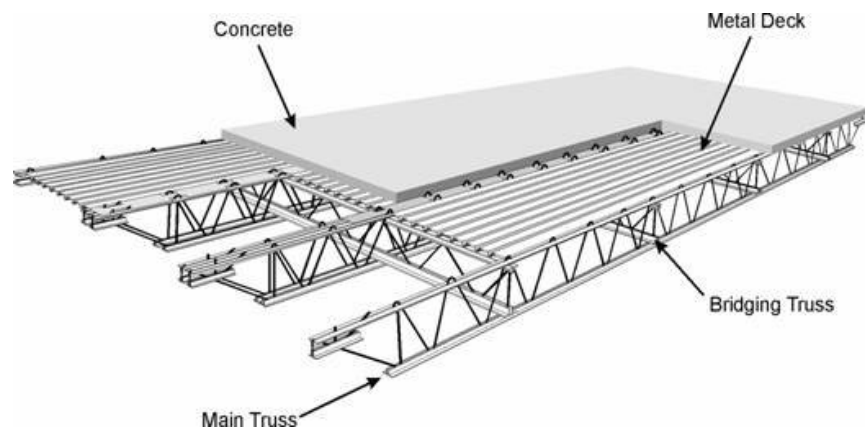


Figure 3: Composite Floor System

There was a "hat truss" atop each tower, intended to support a television antenna on each tower. The hat truss was located within the top few floors and it tied the core to the perimeter columns (Figure 2). There was a 360 feet tall radio and television transmission antenna at the roof of WTC1; no antenna was built on WTC2.

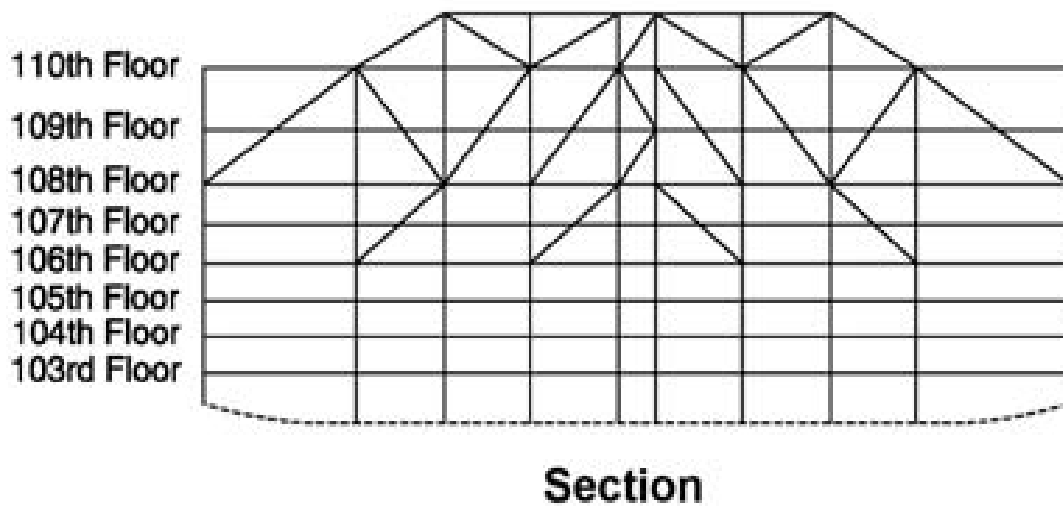


Figure 4: Hat Truss

About 200,000 tons of structural steel was used in the construction of the two towers. Most buildings use no more than two or three different strengths of steel. In contrast, fourteen different strengths of steel were specified in the design of WTC towers (minimum yield strengths of [36, 42, 45, 46, 50, 55, 60, 65, 70, 75, 80, and 100] ksi); but only 12 strengths were actually used because fabricators used 100 ksi steel wherever 85 ksi and 90 ksi steel were specified.

Design documents specified a low strength A 36 steel for floor truss. The steel fabricator instead used a higher strength steel (50 ksi yield strength steel) in the lower chord of the trusses. This might have significantly improved performance at high temperature.

More than a dozen suppliers and fabricators supplied steel for the towers. As a result, even when the different steels met a single specification, their properties could be significantly different. Thus forty different steels were used in the tower structures (various strengths and suppliers).

3. FIRE PROTECTION OF STRUCTURES

The structural steel in the towers was sprayed with fire resistive materials or protected with rigid fire-rated gypsum panels. Sprayed fire resistive materials (SFRMs) are supplied as dry ingredients, and water is added at the time of application. The water mixes with the cementitious materials and allows the SFRM to adhere weakly to the steel. With time, the cementitious materials harden, and excess water evaporates resulting in a covering of insulation with some cohesive strength.

The gypsum panels were used to form fire-protected core columns, stairwells, mechanical shafts, and other fire-protection spaces. Core columns were protected with gypsum panels while the

Some of the details of the analysis of the towers are shown in the figures showing the use of variable-temperature

In addition, the towers were heated to simulate the fire rise and the truss members were heated in

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4. STR

The towers were analyzed for structural response to a Boeing 707 aircraft collision which could result in only local damage which could result in collapse or substantial damage to the building. ...” Since NIST could not locate that aircraft impact analysis report, the method used is not known. In any case, those analysts did not have the advanced structural analysis software available today. We also want to mention that the Boeing 767 planes that hit the towers in 2001 were about 20 percent larger than Boeing 707.

Wind forces were determined on the basis of wind tunnel tests conducted at the Colorado State University and the National Physical Laboratory, United Kingdom. This is now an